# VVER-1000 Reflooding Scenario Simulation with MELCOR 1.8.6 Code in Comparison with MELCOR 1.8.3 Simulation

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2nd European MELCOR User Group Meeting
Prague, Czech Republic, March 1-2, 2010

# Outline

- Motivation
- Comparison of used
  - Codes
  - Models
- Comparison of simulation results
- Reflooding scenario definition
- Visualization of results
- Summary, Conclusions

# Motivation

- Presentation [dsp1] at 5th International QUENCH Workshop (1999) compared simulation of MELCOR 1.8.3 and ICARE2 V2-Mod2.3 simulation for reflooding scenario of VVER-1000
- Several simulations of Quench tests performed with MELCOR (1.8.5 and 1.8.6) and also with ICARE2
  - Quench-01 (M5, M6, I2), Quench-03 (M5, I2), Quench-06 (M5), Quench-07 (M6), and Quench-11 (M6)
- Interest to see progress in simulation of reflooding scenario with MELCOR code during last 10 years

[dsp1] J. Duspiva: VVER-1000 Core Quenching Analyses with MELCOR and ICARE Codes, 5th International QUENCH Workshop, Karlsruhe, October 19-21, 1999

# Comparison of Codes MELCOR 1.8.3 to MELCOR 1.8.6

- MELCOR 1.8.3 was released in 1994 and MELCOR 1.8.6 in 2006
  - Version of MELCOR 1.8.6 YU_2911 used in the simulations was released in August 2009
- New model capabilities in MELCOR 1.8.6 in comparison with MELCOR 1.8.3
  - Reflooding model
    - Distinguished wetted and non-wetted surface temperature of components within individual COR cell
    - Position of quench front on surface of structures (mainly CL)
  - Distinguished supporting (core support plate) and non-supporting structures (guide tubes and control rods)
  - Core structure loading and failure modeling
  - New shroud and core former components in COR package
  - Melting of boundary HS
  - Molten pool models – in core and in lower plenum, oxidic and metallic
  - Lower head failure modeling
  - Control rod degradation improved for both SIC and B4C, and others
- Progress in computer power resulted in possibility to use significantly more detailed nodalization

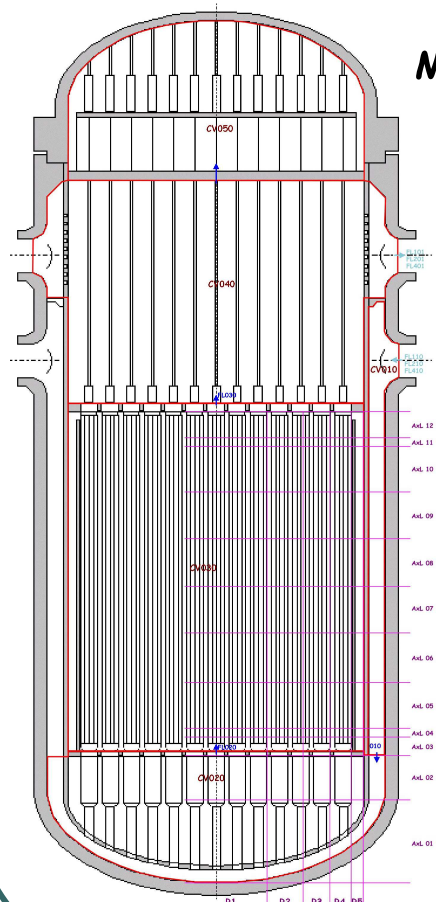
# Comparison of Models MELCOR 1.8.3 to MELCOR 1.8.6

**Comparison of nodalization – three cases compared**

| Number of input objects | MELCOR 1.8.3 | MELCOR 1.8.6 | MELCOR 1.8.6 detailed COR |
|---|---|---|---|
| CV – total | 69 | 129 | 187 |
| CV – Cntn | 5 | 29 | 29 |
| CV – IO | 30 / 3 loops | 30 / 3 loops | 30 / 3 loops |
| CV – IIO | 14 | 24 | 24 |
| CV – RPV | 5 | 7 | 65 |
| COR – Total/#Ring | 60 / 5 rings | 217 / 7 rings | 217 / 7 rings |
| FL – Total | 106 | 198 | 318 |
| HS – Total | 190 | 379 | 379 |
| RN Classes | 16 | 25 | 25 |

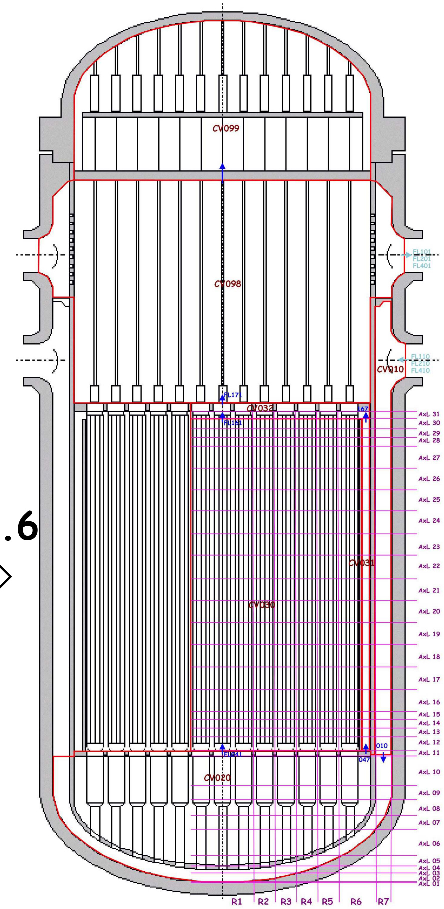
Figures prepared only for RPV, because this part is the most interesting for reflooding topic

# Comparison of Models MELCOR 1.8.3 to MELCOR 1.8.6 (2)



MELCOR1.8.3

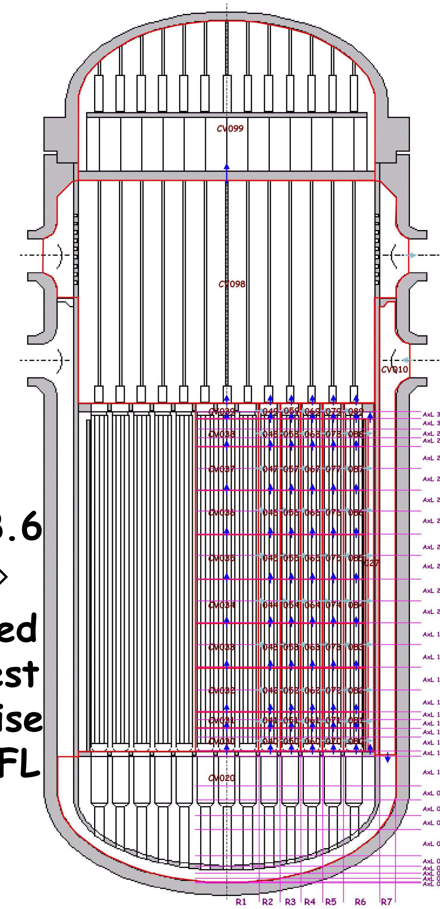
⇦



MELCOR1.8.6

⇨

standard approach



MELCOR1.8.6

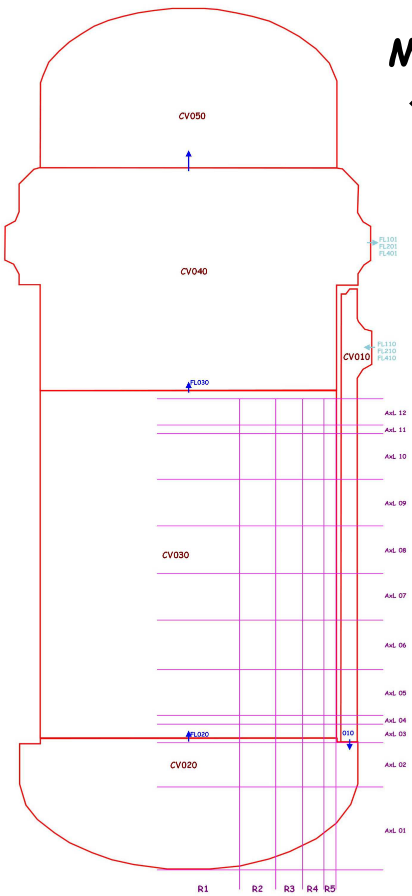
⇨

recommended best practise detailed CV/FL

Reactor Pressure Vessel Nodalization – RPV Figure, COR, CVH/FL Packages

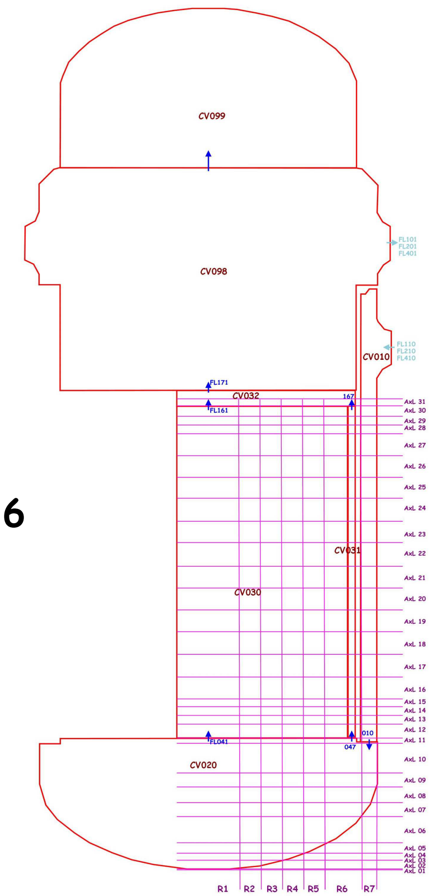
# Comparison of Models MELCOR 1.8.3 to MELCOR 1.8.6 (3)

MELCOR1.8.3 ⇦



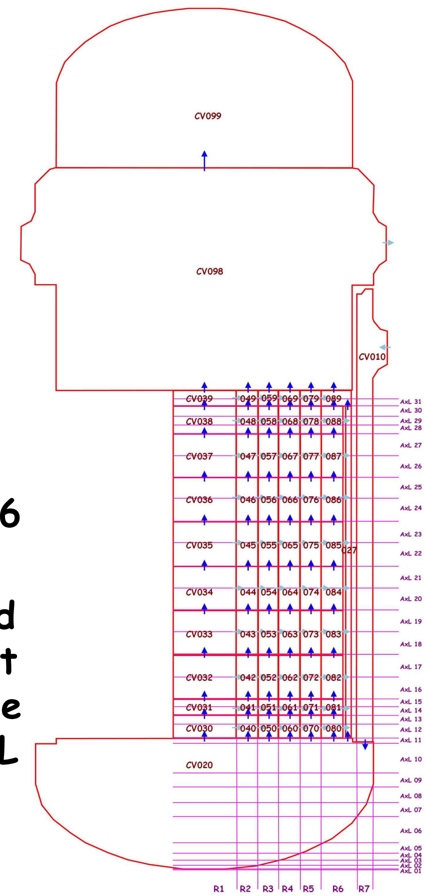

MELCOR1.8.6 ⇨

standard approach



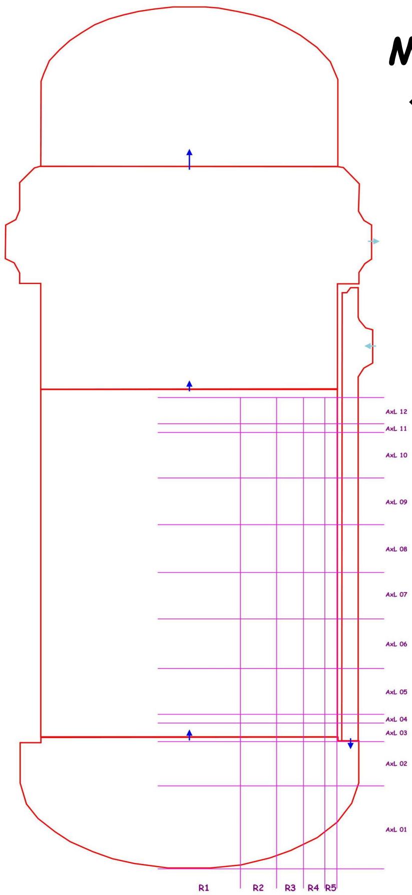

MELCOR1.8.6 ⇨

recommended best practise detailed CV/FL



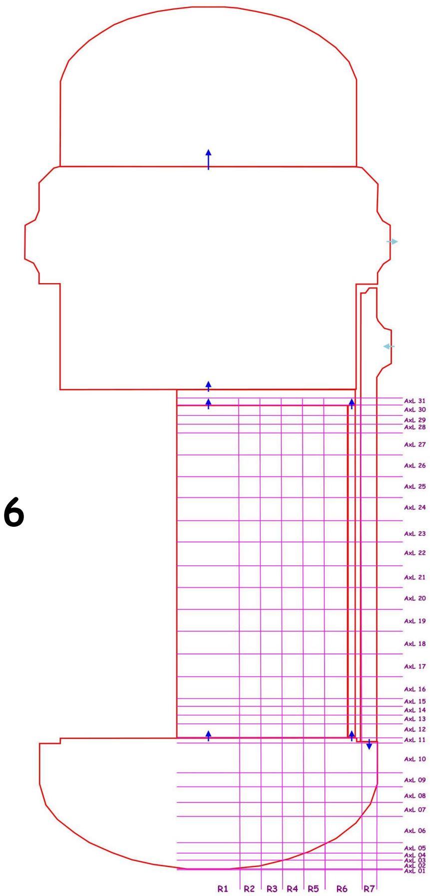

Reactor Pressure Vessel Nodalization – COR, CVH/FL Packages

# Comparison of Models
# MELCOR 1.8.3 to MELCOR 1.8.6 (4)

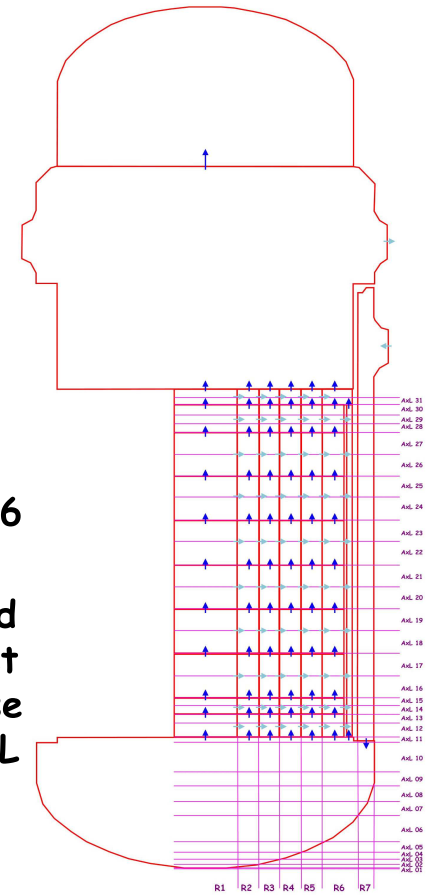


MELCOR1.8.3 ⇦

MELCOR1.8.6 ⇨ standard approach



MELCOR1.8.6 ⇨ recommended best practise detailed CV/FL



**Reactor Pressure Vessel Nodalization – COR, CVH/FL Packages**

# Comparison of Models MELCOR 1.8.3 to MELCOR 1.8.6 (5)

**MELCOR 1.8.3 COR Model for VVER-1000**

- PWR type
- 5 Rings
  - 4 rings with fuel and
  - 5th ring - core baffle modelled with other str.
  - Core barrel modelled as axial boundary HS
- Only 1 CV covers whole core
- Spacer grids modelled as part of cladding
- Control rods modelled as other str.
- Supporting or non-supporting feature distinguished only with parameter ISUP (input row CORZij02)
  - This option is defined for all components in axial level
- Lower plenum internals modelled as OS
- LHF – temperature criterion on outer surface
  - User model

**MELCOR 1.8.6 COR Model for VVER-1000**

- PWR type
- 7 Rings
  - 6 rings with fuel, but
  - 6th ring splitted into channel (FU) and bypass with SH component (core baffle)
  - 7th ring only in lower plenum
- 3 or 67 CVs cover whole core (incl. bypass)
- Spacer grids modelled as supporting structure with temperature condition of its failure
  - User defined type with options
    - Intact and debris
- Control rods modelled as NS
  - Advanced model applied
- SH component modelled with "Fixed" option
  - Available from M186 YT_1010 version
- Lower Plenum internal modelled as user defined SS
- LHF – zero dimensional model (LH has no insulation)

# Reflooding Scenario Definition
## Large LOCA

- **Initiating Event**
  - Large break LOCA on the surge line between a hot leg of the primary circuit and the pressurizer with equivalent diameter 200 mm
- **Subsequent events**
  - Loss of active emergency core cooling systems
  - Loss of two of four HAs (one of them supplying water into down comer and the second one into upper plenum)
- **Interruption of accident progression**
  - Restoration of one train of the high-pressure core cooling system in injection phase at the time 2200 s (system is connected into Cold Leg between MCP and RPV) – $T_{CL\text{-}MAX}$ about 1200 K
  - Successfully switched to recirculation phase at the time 2450 s (heat exchanger is operating)
  - Water mass flow rate of restored HPI is about 57 kg/s in both phases
  - Temperature of HPI water is 60 °C in injection and from 35 to 38 °C during recirculation

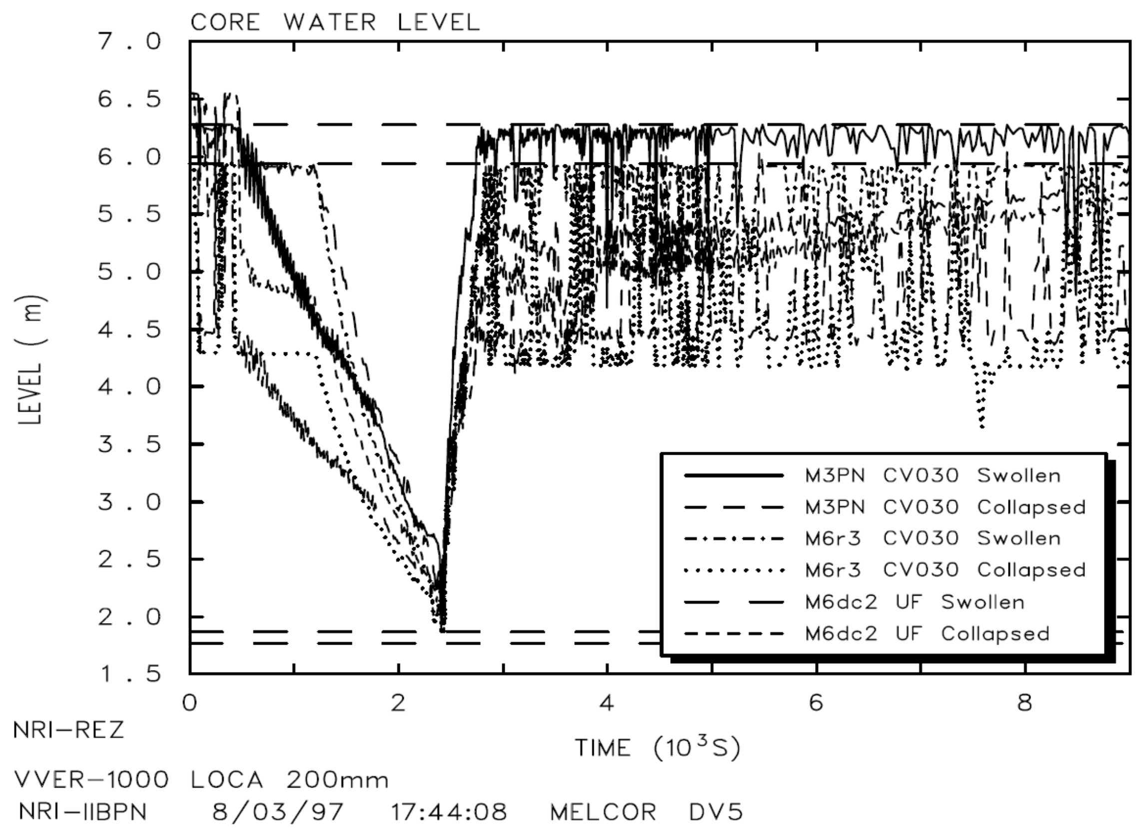
Time Table of Main Event
(MELCOR 1.8.3 Results)

| Event | | Time [s] |
|---|---|---|
| Initiating Event and SCRAM | … | 0 |
| Start of One Train of Containment Spray System | … | 55 |
| Start of HA | … | 170 |
| End of HA | … | 410 |
| Ring 2 Fuel Cladding Failure | … | 1973 |
| Ring 3 Fuel Cladding Failure | … | 1982 |
| Ring 1 Fuel Cladding Failure | … | 2021 |
| Start of HPI in Injection Phase | … | 2200 |
| Water Level on Bottom of Fuel | … | 2420 |
| HPI Switched to Recirculation | … | 2450 |
| Ring 4 Fuel Cladding Failure | … | 2454 |
| Water Level on Top of Fuel (End of Quenching) | … | 2470 |
| End of Calculation | … | 9000 |

- Timing of main events slightly different between MELCOR 1.8.3 and 1.8.6 simulations
  - Start of HPI in injection phase changed to 2100 s in MELCOR 1.8.6 simulation to keep identical timing of water injection into core at 2420 s

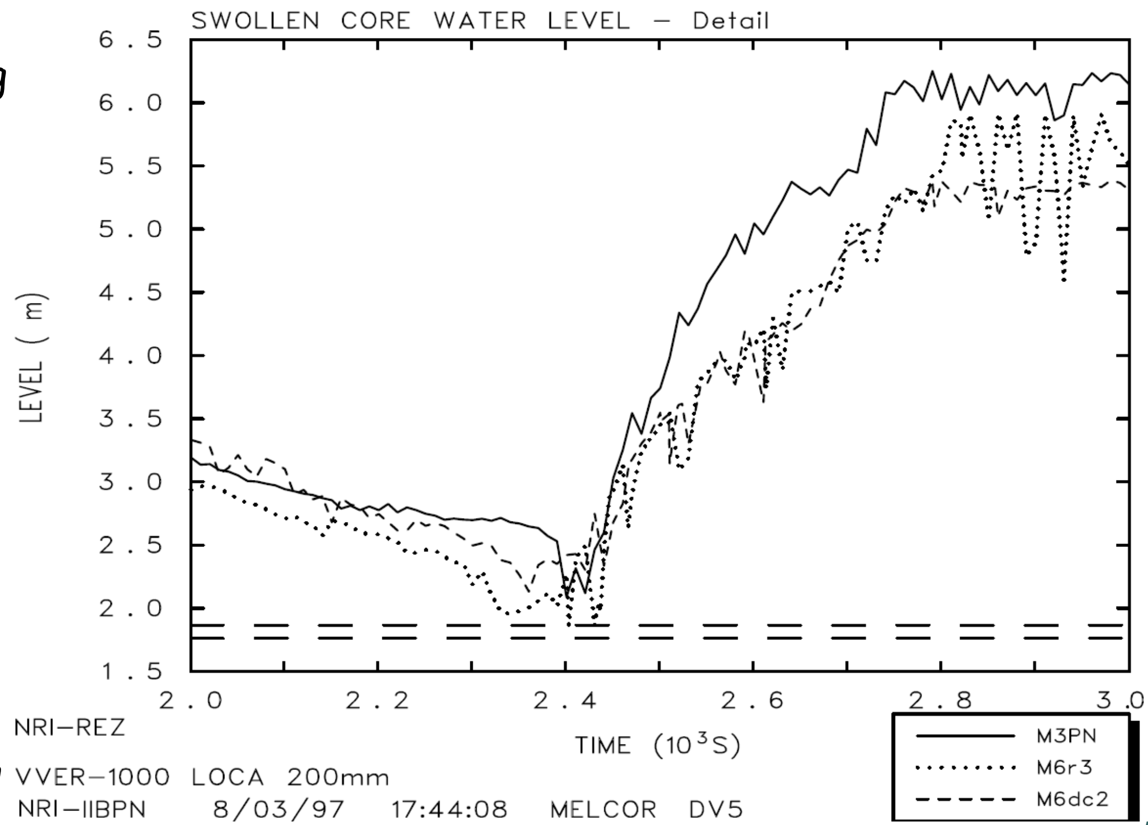
# Comparison of Results
## Water Levels in Core

- Different boil off phase
  - M183 – earlier starting of core uncovery with slower water level falling
- Reflooding initiated at same time – boundary condition of comparison
- Water level rise
  - M183 faster swollen level
  - M183 slower collapsed level
- M6dc2 – slow rise in long term



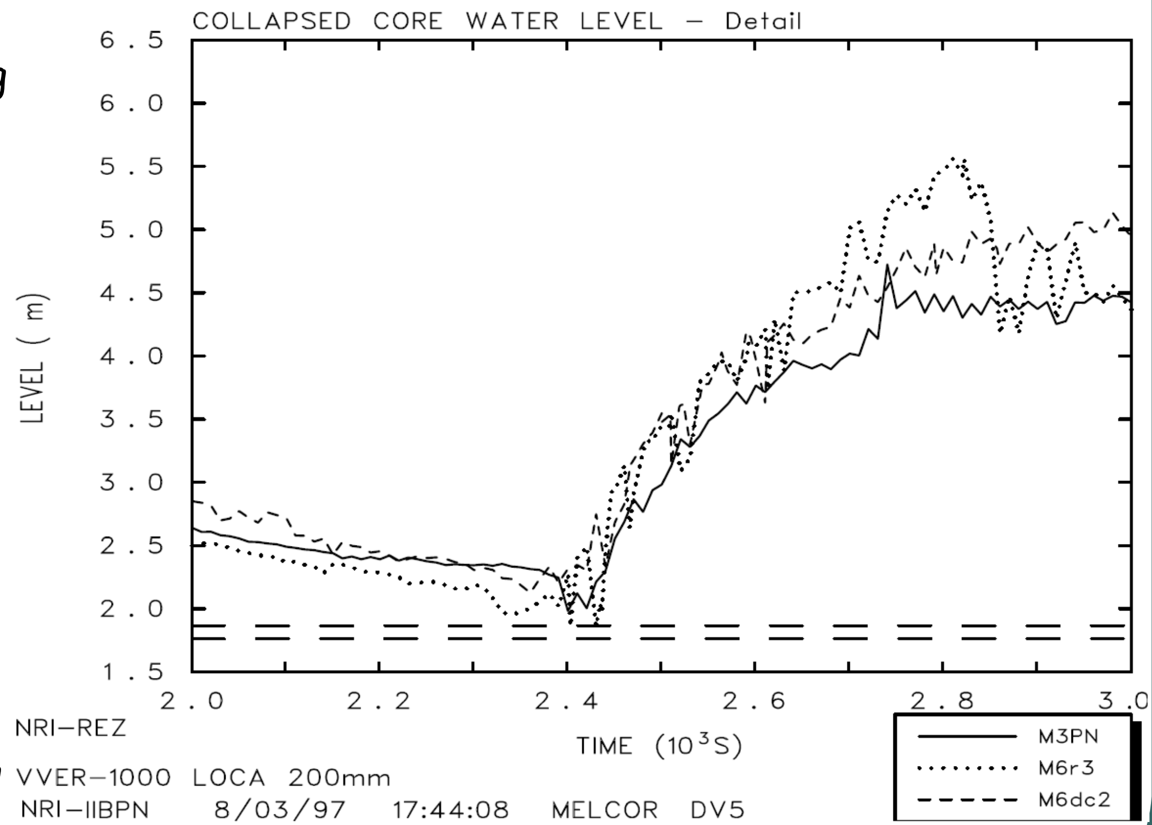
# Comparison of Results
# Swollen Water Levels in Core (2)

- Different boil off phase
  - M183 – earlier starting of core uncovery with slower water level falling
- Reflooding initiated at same time – boundary condition of comparison
- Water level rise
  - M183 faster swollen level
  - M183 slower collapsed level
- M6dc2 – slow rise in long term



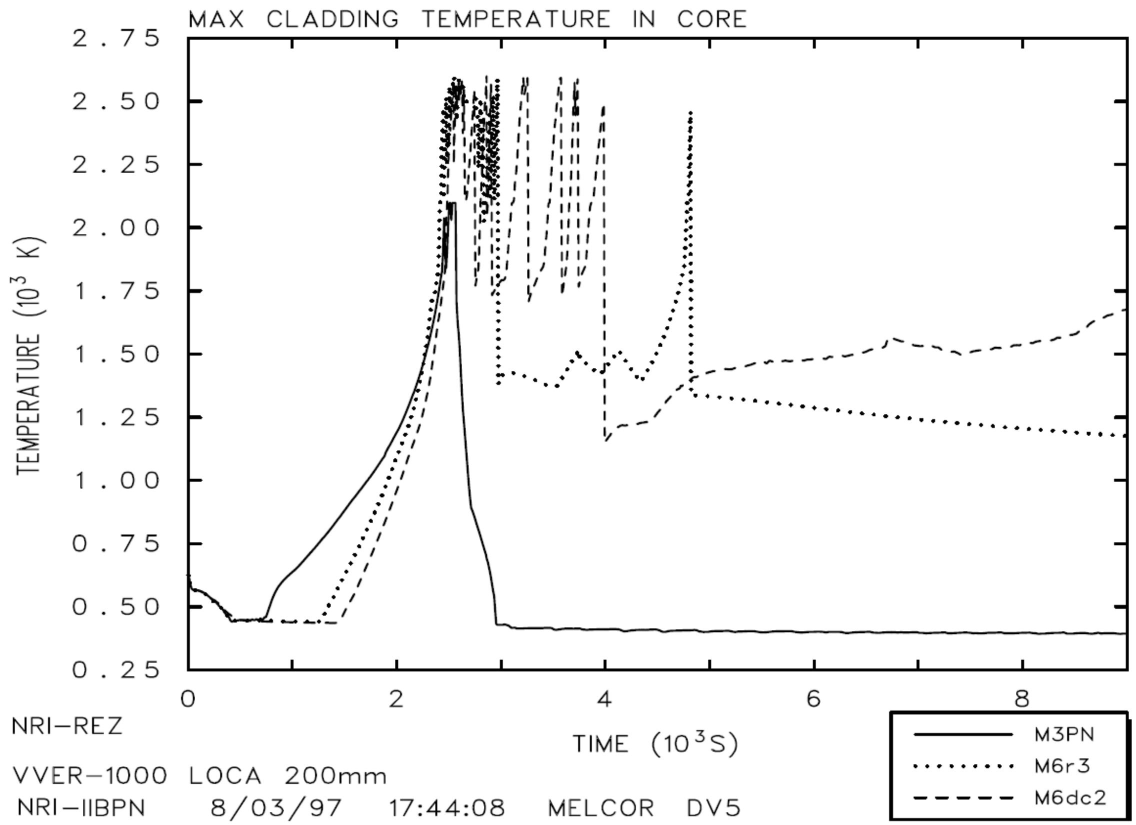
# Comparison of Results
# Collapsed Water Levels in Core (3)

- Different boil off phase
  - M183 – earlier starting of core uncovery with slower water level falling
- Reflooding initiated at same time – boundary condition of comparison
- Water level rise
  - M183 faster swollen level
  - M183 slower collapsed level
- M6dc2 – slow rise in long term



# Comparison of Results
## Cladding Maximum Temperature (1)

- Overall heat generation by fission and decay power identical
- Different treatment of energy transfer from COR to CV
  - Impact of version
  - Impact of nodalization (core periphery and radial heat losses)
- Difference in heat generation by oxidation
- More intensive heat up in M186 simulations is in accordance with ICARE2 [dsp1] or SCDAP/RELAP5 simulations [dsp2]

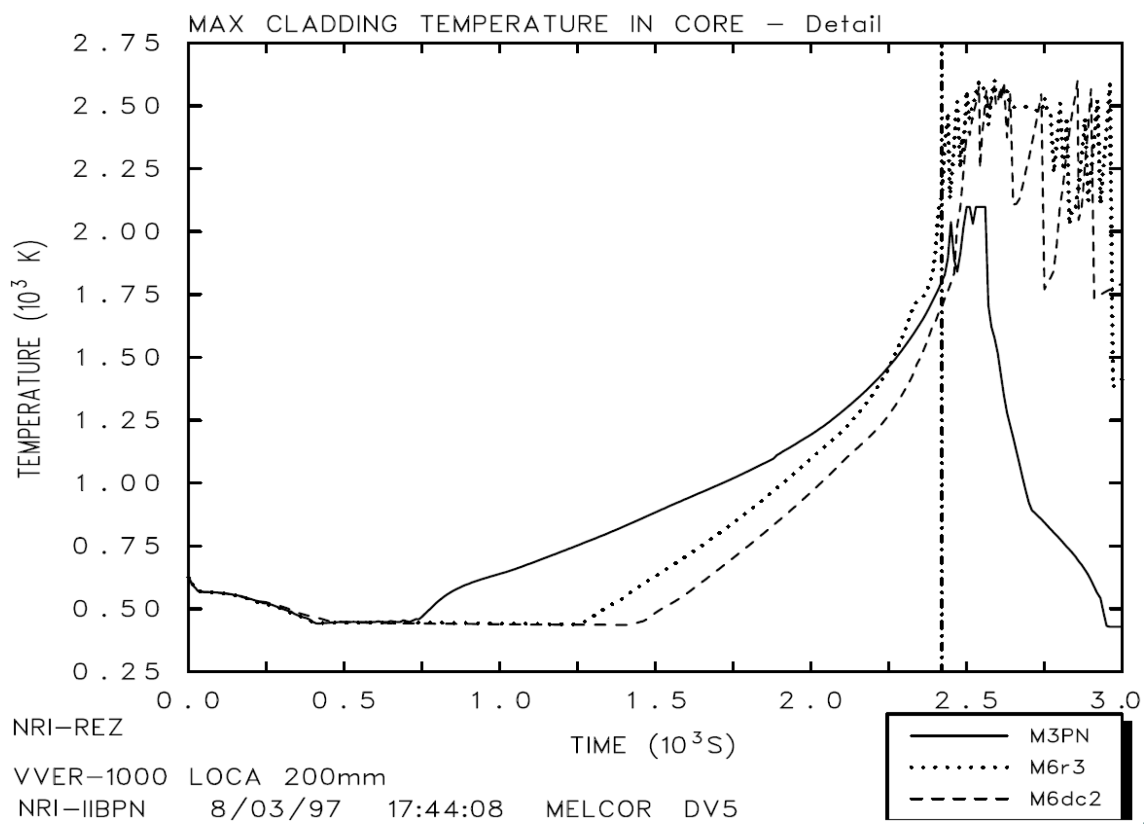




[dsp2] J. Duspiva: MELCOR1.8.5 and SCDAP/RELAP5 Codes Validation and Revision of MAAP Models; Validation Exercises LBLOCA-M and LBLOCA-S, Report UJV 11970-T, September 2002 (in Czech)

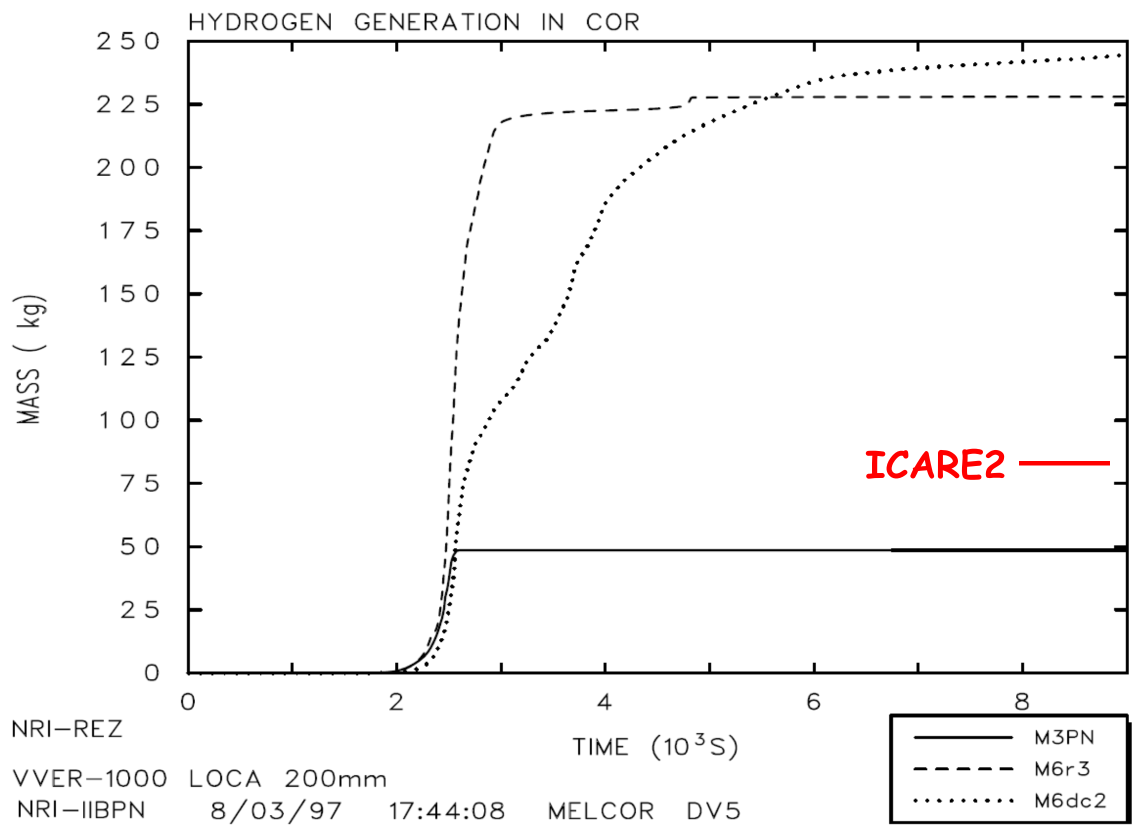
# Comparison of Results
## Cladding Maximum Temperature (2)

- Water ingress into core starts at 2420 s (dot-dash vertical line)
- Very different maximum temperatures predicted
  - M3PN 1801.7 K
  - M6r3 2142.6 K
  - M6dc2 1699.2 K
- That is consequence of different oxidation before reflooding onset
  - M3PN 20.228 kg of H2
  - M6r3 27.222 kg of H2
  - M6dc2 12.578 kg of H2



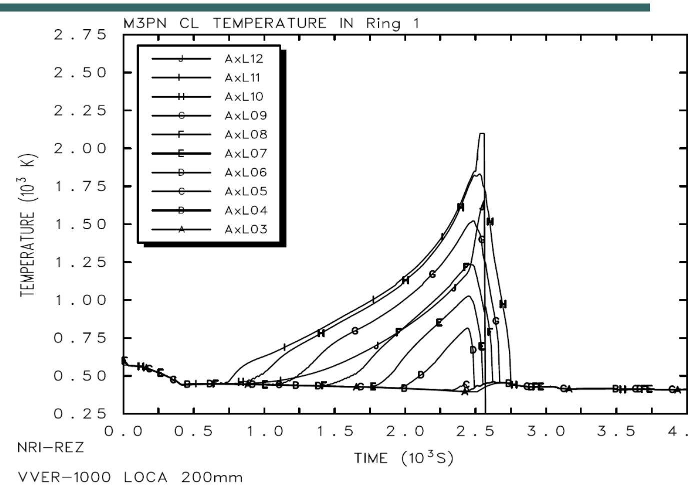
# Comparison of Results
## Hydrogen Generation

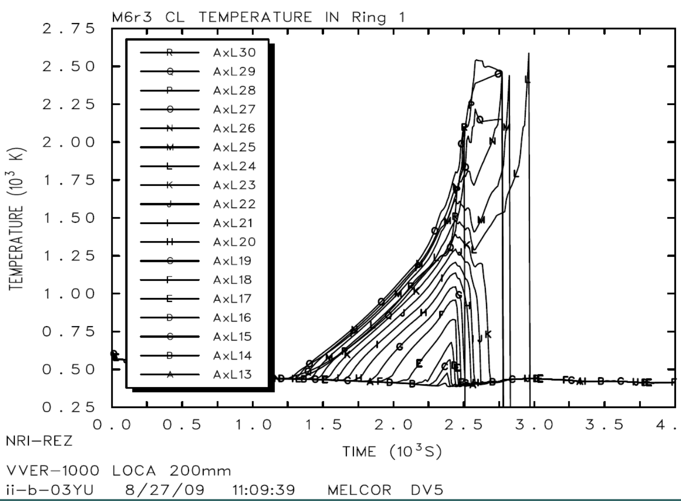
- The highest hydrogen generation during reflooding predicted in M6r3 case due to significantly higher temperature at reflooding onset
- M183 without reflooding model significantly underestimated hydrogen generation
  - ICARE2 [dsp1] 80.75 kg
- Steam starvation condition indicated during beginning of reflooding
  - Short period in M183 a M6r3
  - Longer time period in M6dc2 – long time in some nodes

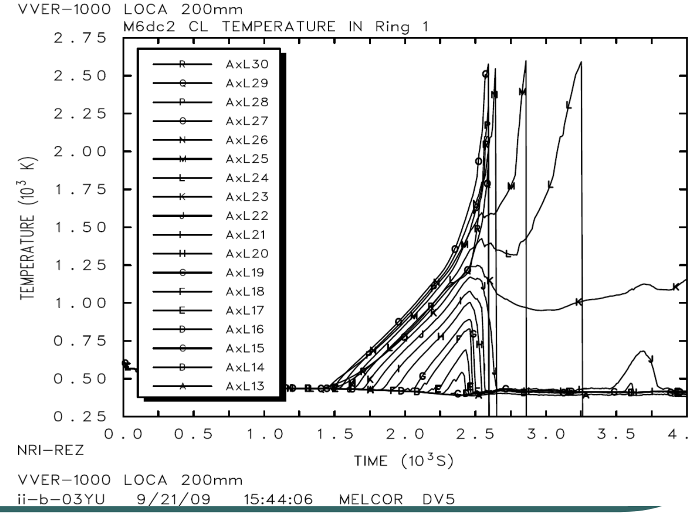


# Comparison of Results
## Temperatures in Core – Ring 1

- Different nodalization in M183 and M186
  - Rings do not represents identical part of core
- Ring 1
  - M6dc2 – molten pool is not cooled down and cladding temperature in node below it is slowly rising

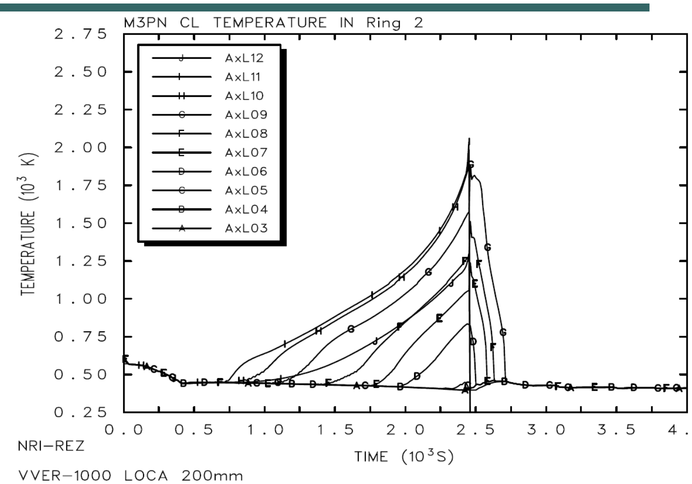


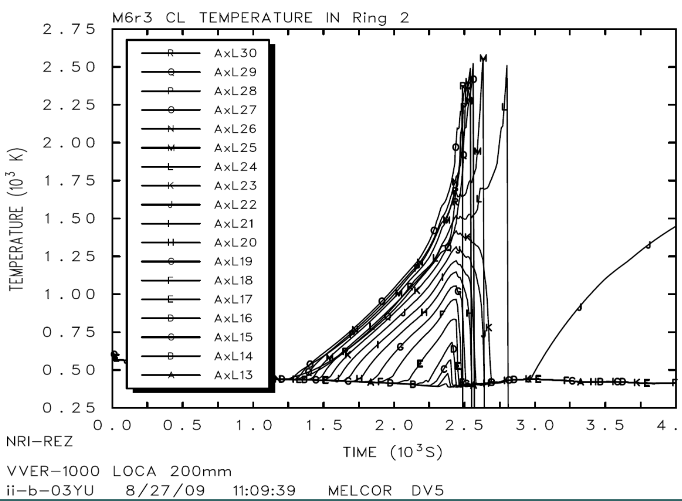



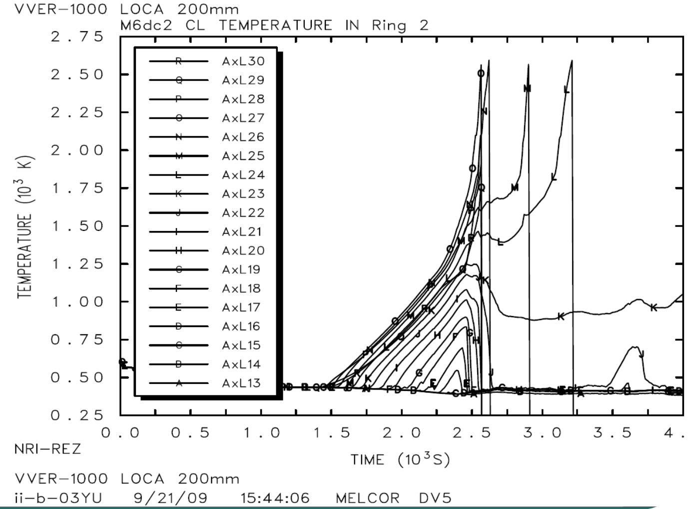



# Comparison of Results
# Temperatures in Core – Ring 2

- Different nodalization in M183 and M186
  - Rings do not represents identical part of core
- Ring 2
  - M6dc2 – molten pool is not cooled down and cladding temperature in node below it is slowly rising
  - M6r3 – AxL22 collapsed at about 4500 s and debris cooled down

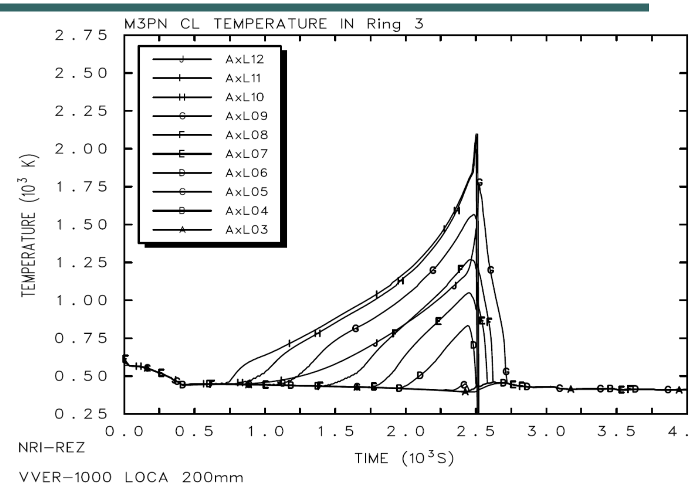


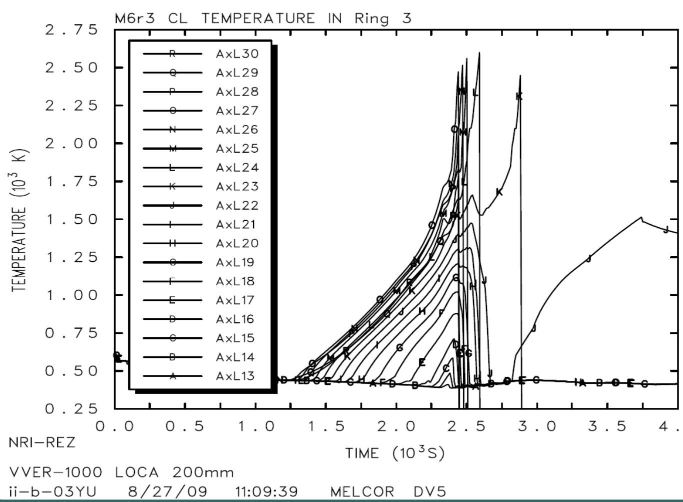



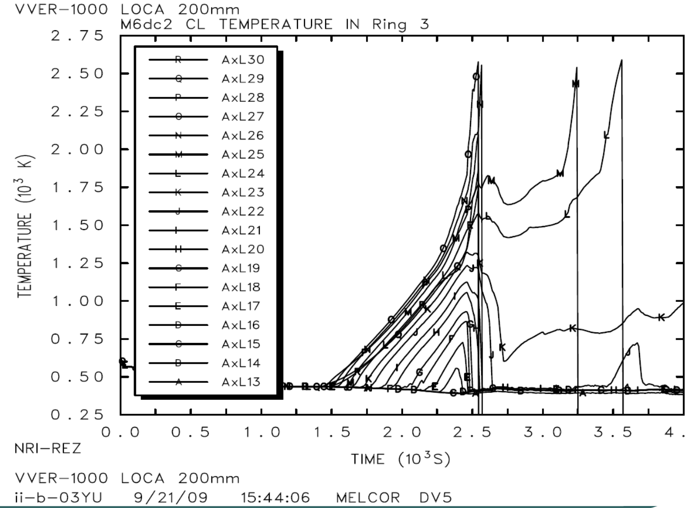



# Comparison of Results
## Temperatures in Core – Ring 3

- Different nodalization in M183 and M186
  - Rings do not represents identical part of core
- Ring 3
  - M6dc2 – molten pool is not cooled down and cladding temperature in nodes below it are slowly rising, also radial relocation influences temperature evolution (change of trend from cooling to heat up)

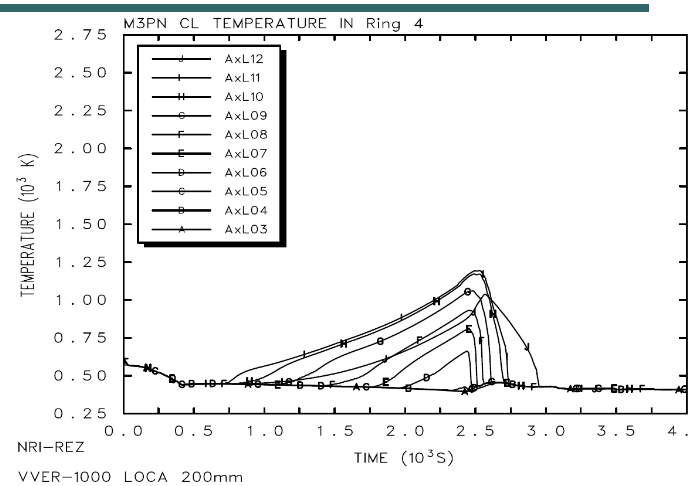


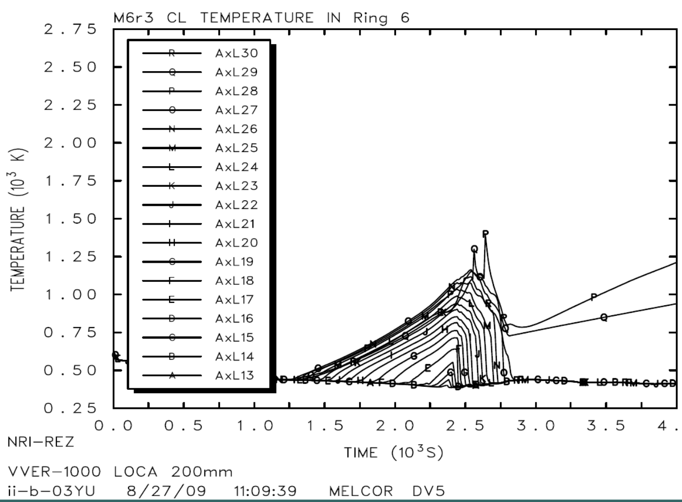



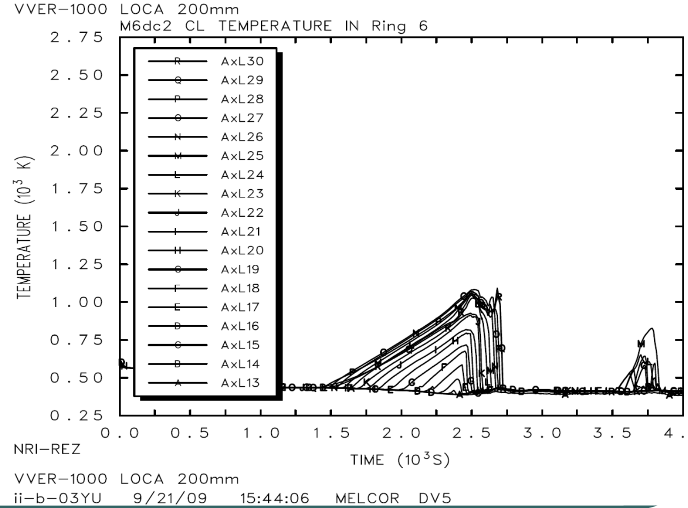



# Comparison of Results
## Temperatures in Core – Outermost Ring

- Different nodalization in M183 and M186
  - Rings do not represents identical part of core
- Ring 4 in M183 and Ring 6 in M186
  - M6dc2 and M6r3 – behavior influenced by radial relocation of hot debris

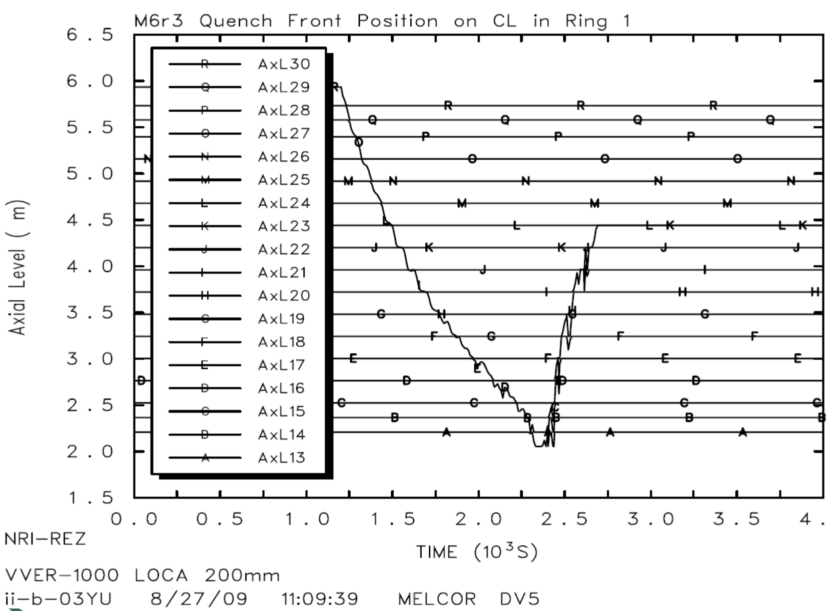


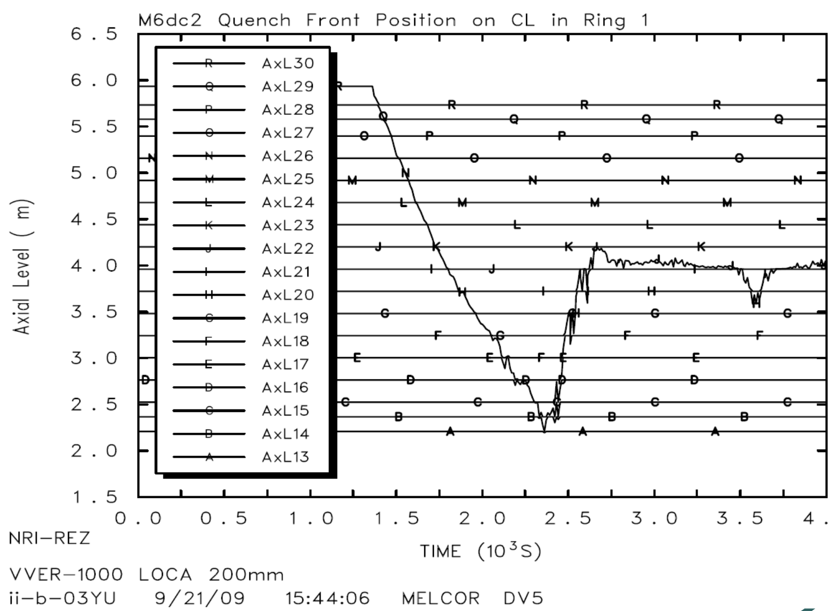



# Comparison of Results
# Quench Front Position

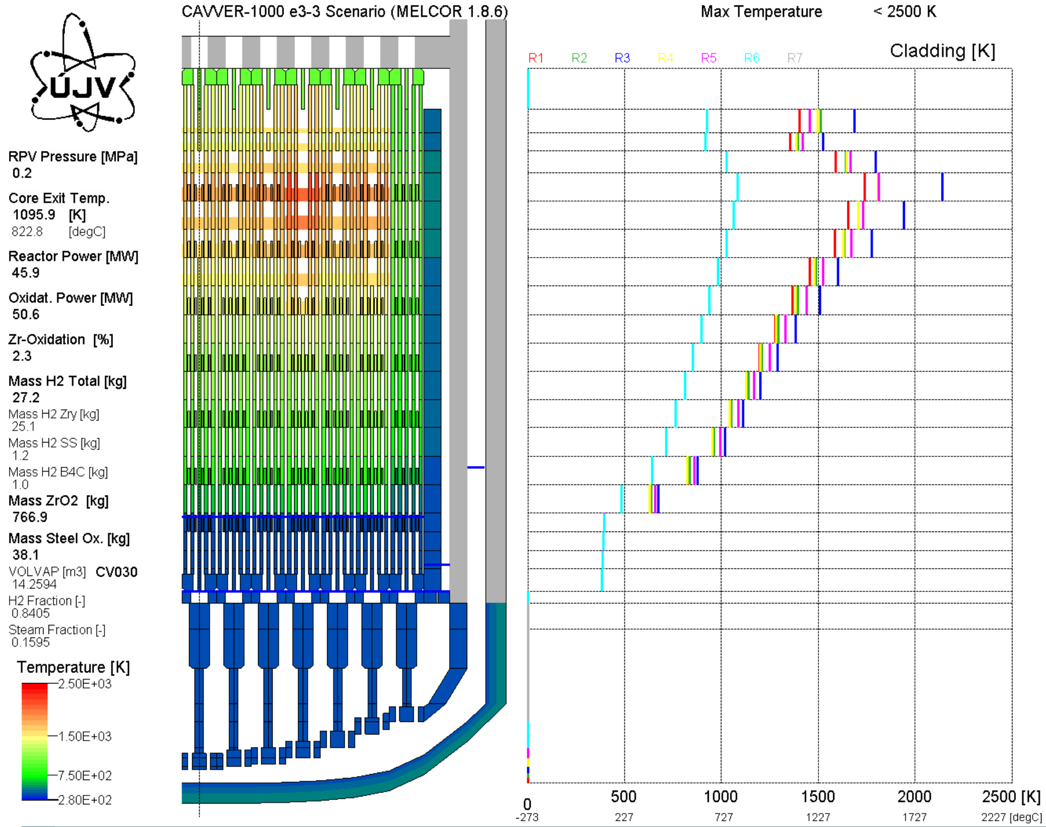
- MELCOR with reflooding model calculates quench front position on surface of COR components – CL is the most important
  - This output not available in MELCOR 1.8.3
  - Earlier initiation of front falling in M6r3 case
  - Molten pool in M6dc2 case is not fully cooled down



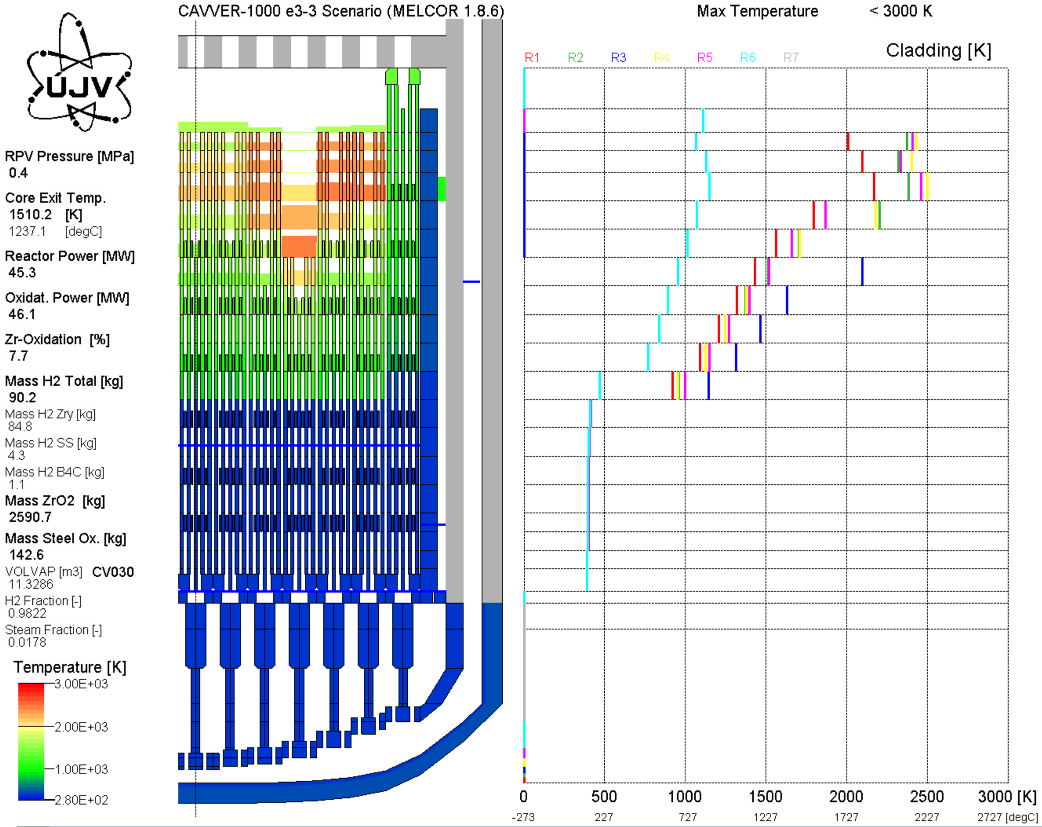
# M186r3 Case Results
## Bundle Configuration (1)

- **Time 2420 s** – just before reflooding;
- Control rod degradation started in hot spot



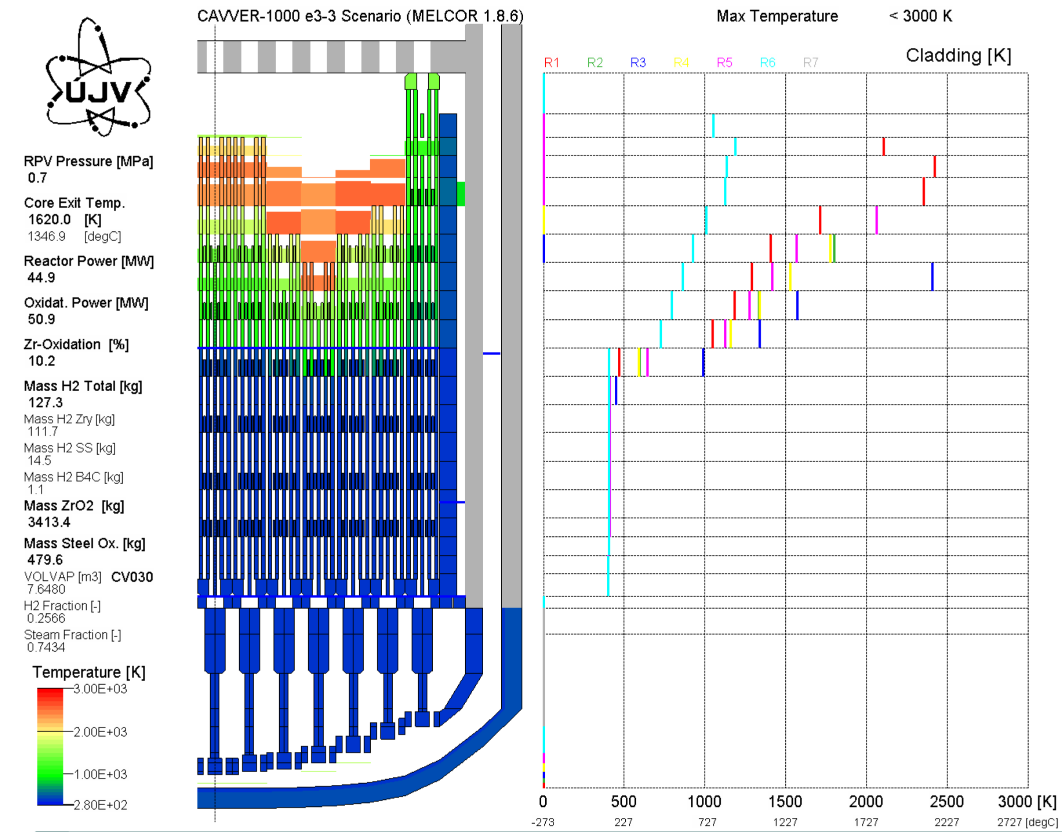
# M186r3 Case Results
# Bundle Configuration (2)

- **Time 2520 s**
- Upper part of fuel assemblies in R1 –R5 relocated



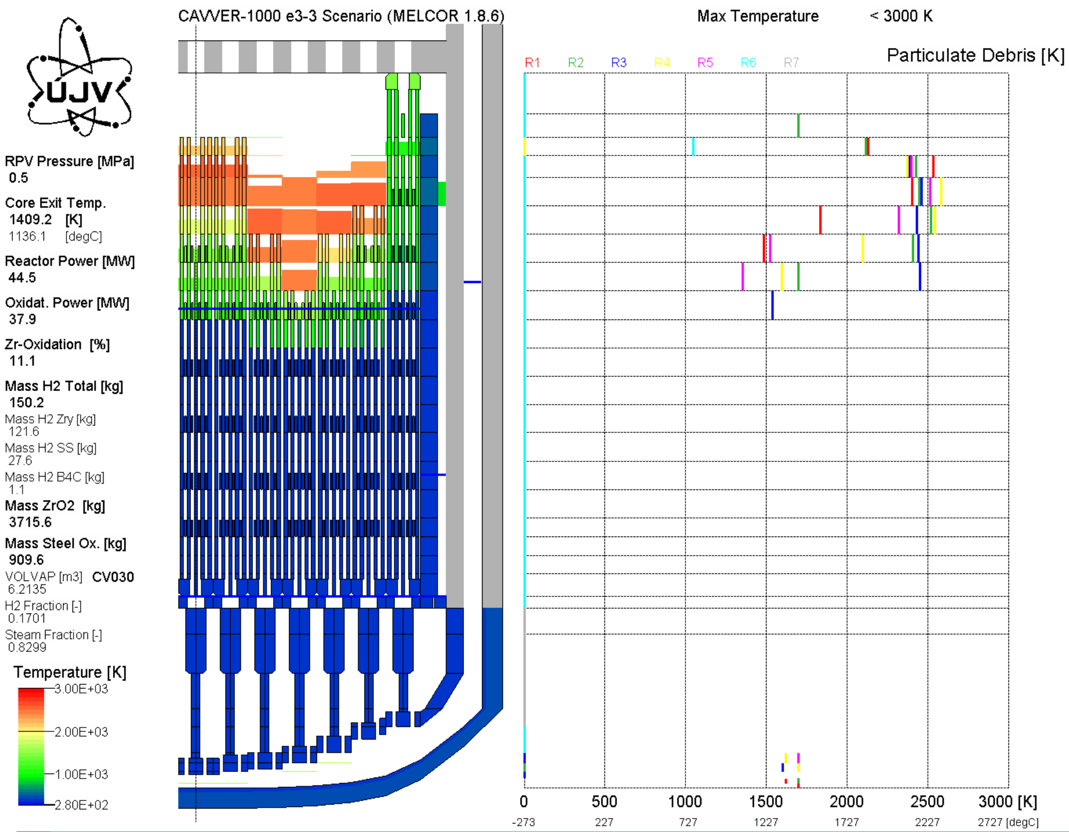
# M186r3 Case Results
## Bundle Configuration (3)

- **Time 2570 s**
- Formation of debris bed in R1 –R5 relocated



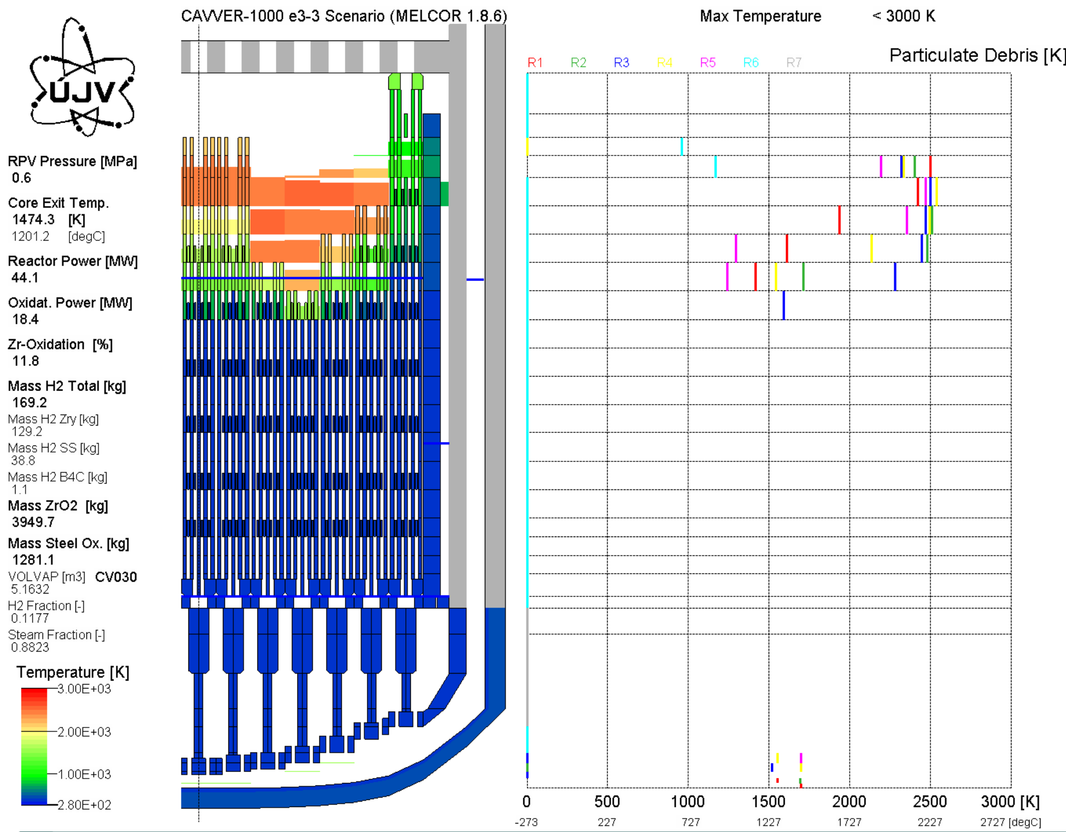
# M186r3 Case Results
## Bundle Configuration (4)

- **Time 2620 s**
- Formation of debris bed in R1 –R5 relocated



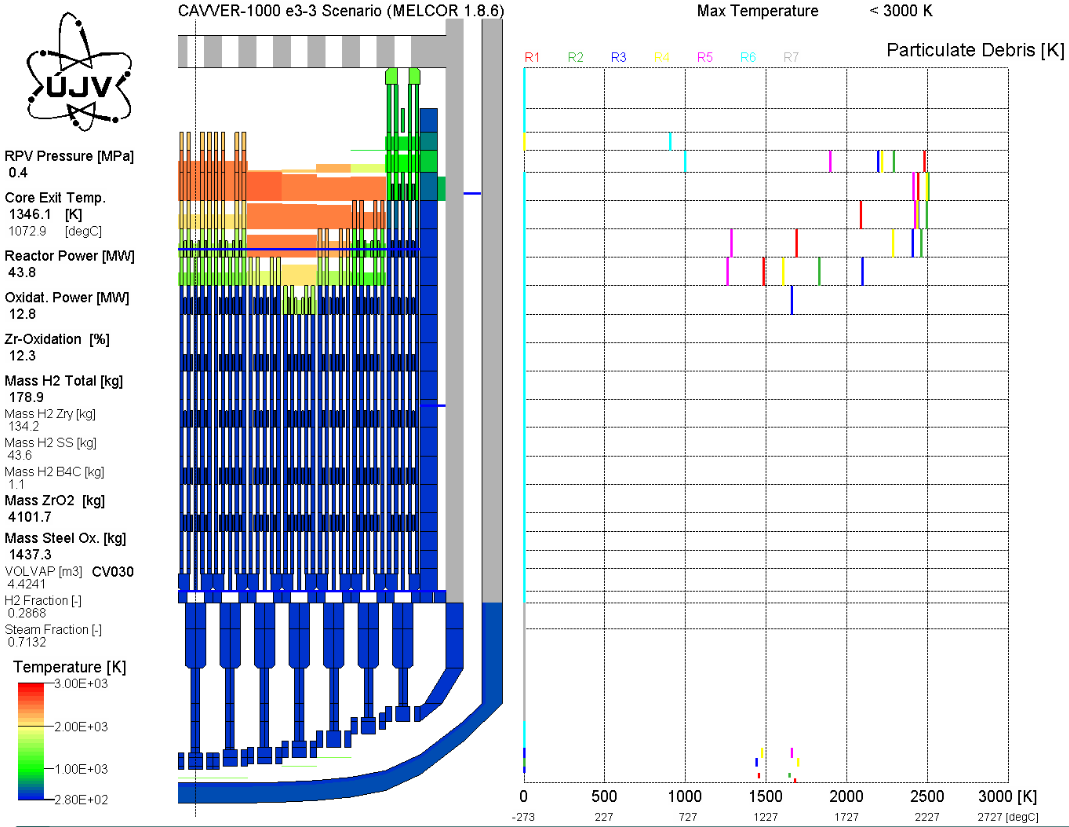
# M186r3 Case Results
## Bundle Configuration (5)

- Time 2670 s
- Water at elevation of debris bed bottom



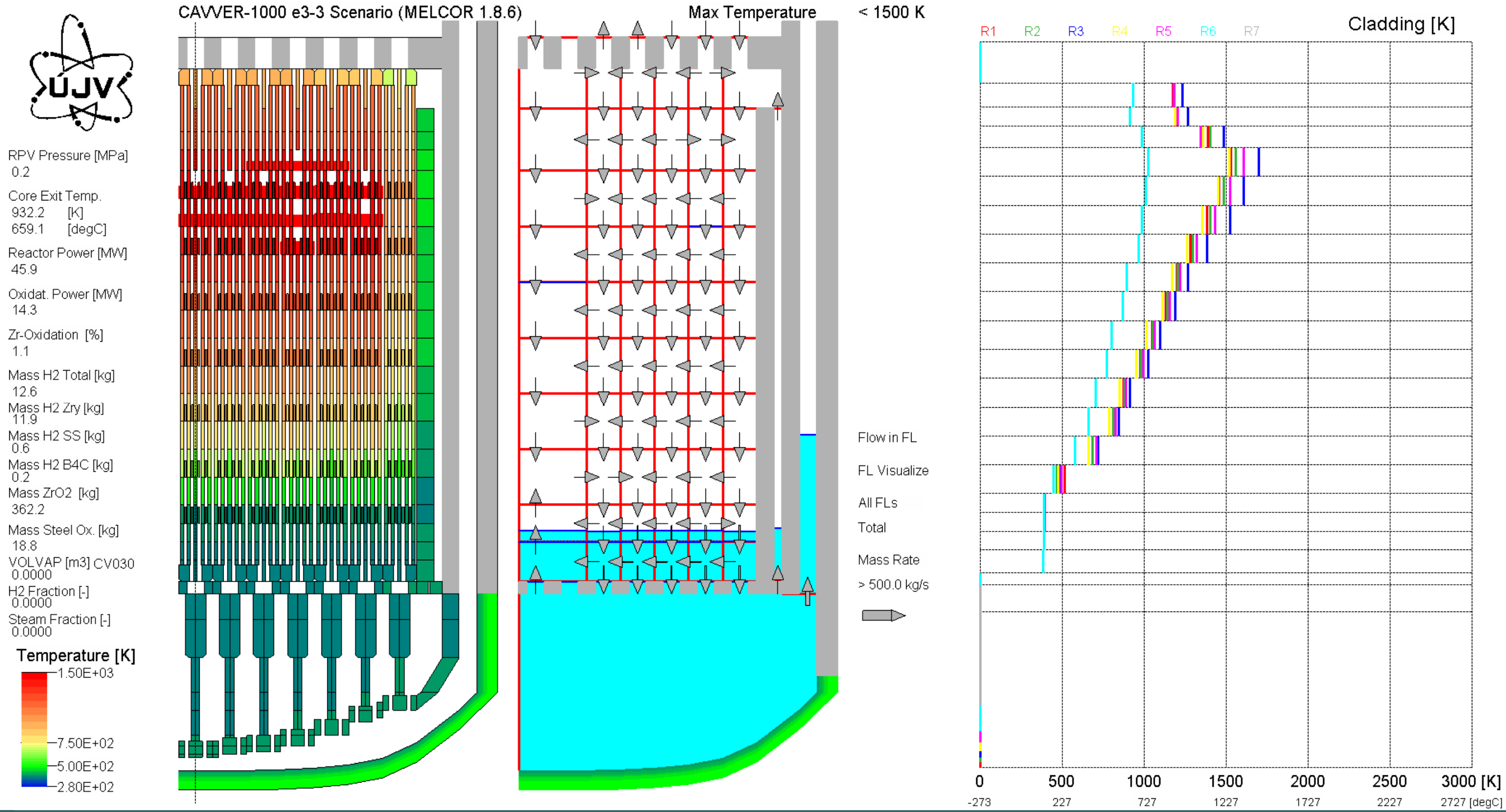
# M186r3 Case Results
# Bundle Configuration (6)

- **Time 2720 s**
- Cooling of debris bed started



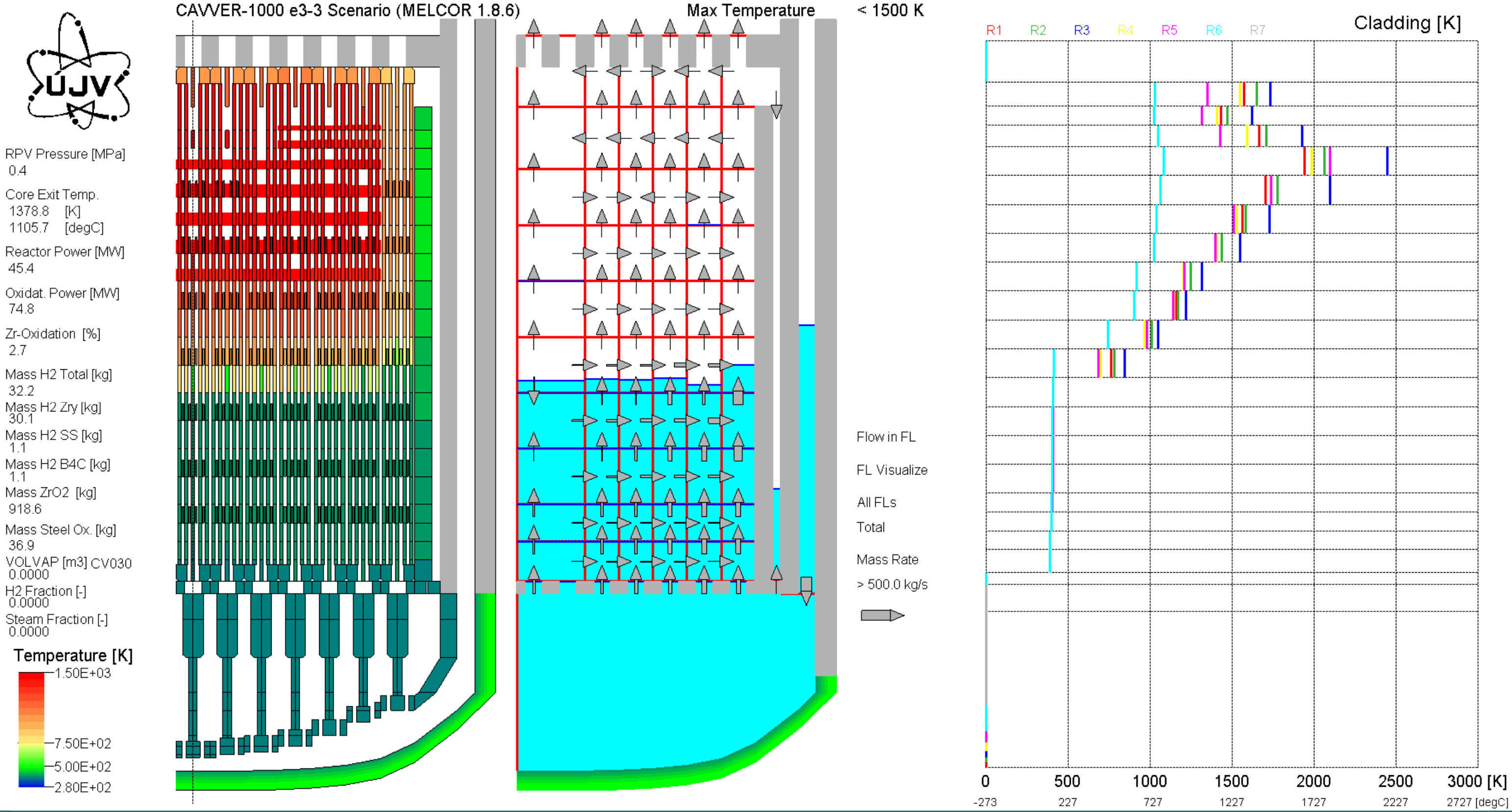
# M186dc2 Case Results
## Bundle Configuration (1)

- **Time 2420 s** – just before reflooding
- Control rod degradation started in hot spot (like in M6r3 case)



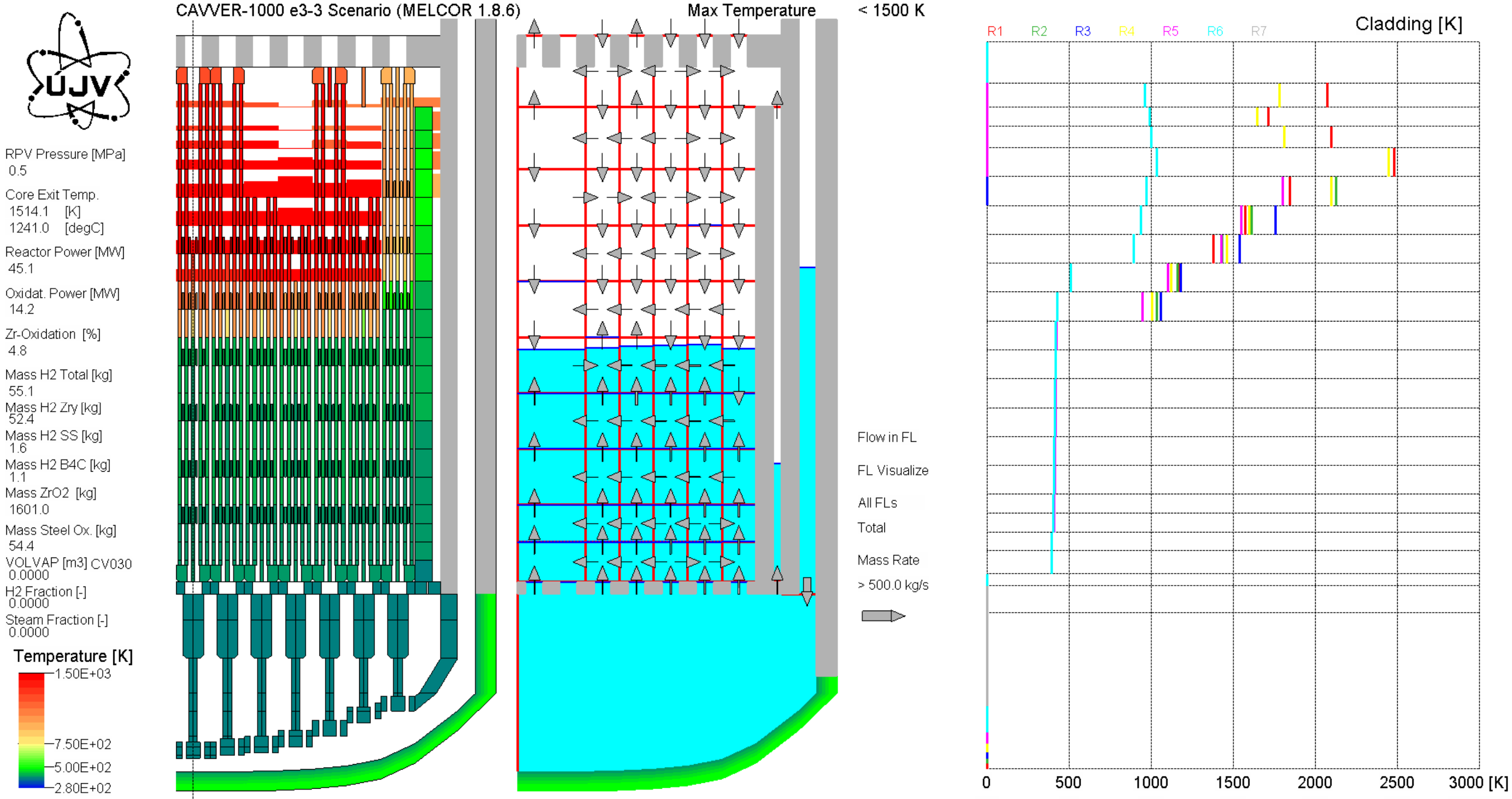
# M186dc2 Case Results
## Bundle Configuration (2)

- **Time 2520 s**
- Fuel rod relocation did not yet start



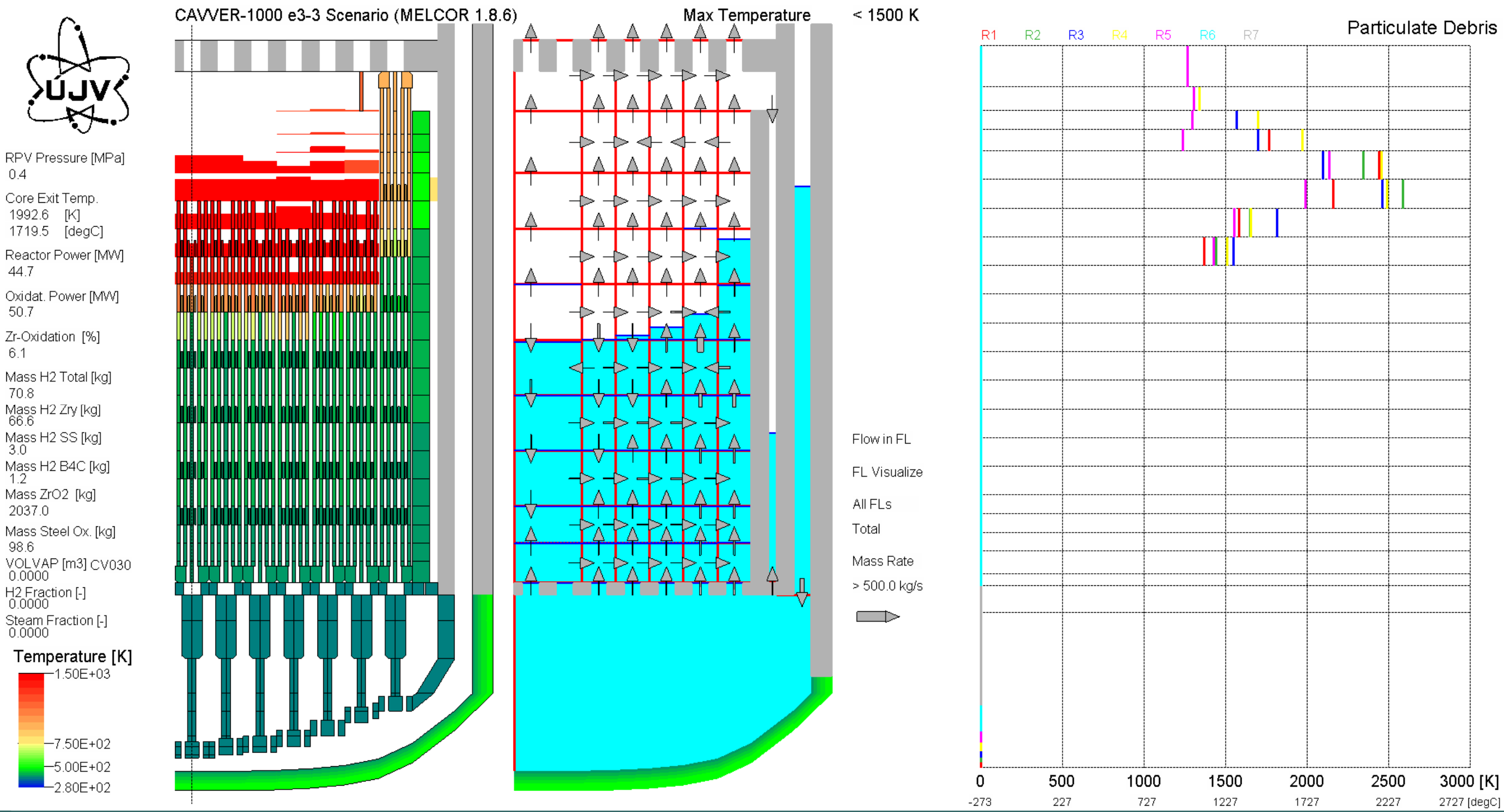
# M186dc2 Case Results
## Bundle Configuration (3)

- **Time 2570 s**
- Upper part of fuel assemblies in R1 –R5 relocated



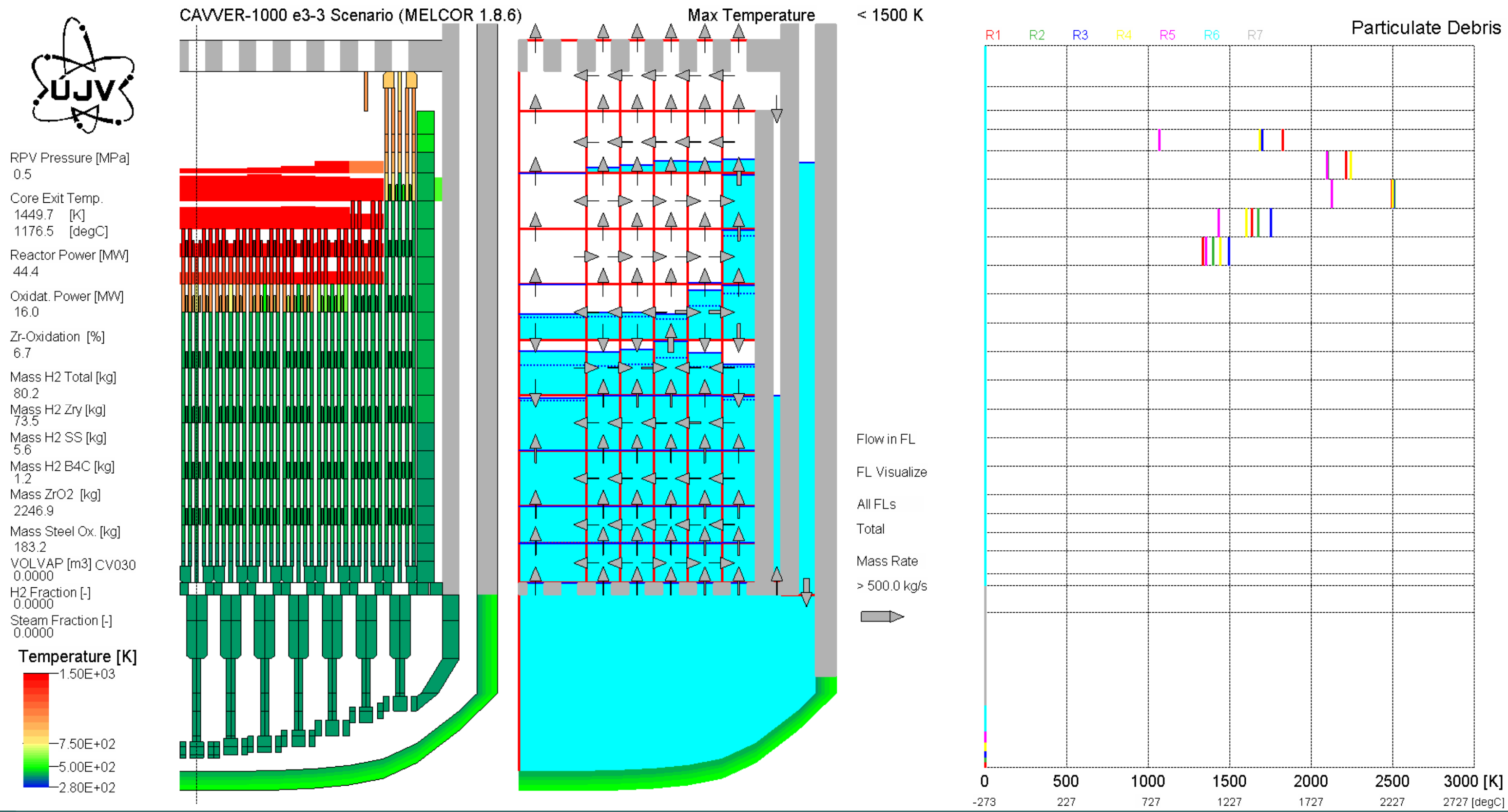
# M186dc2 Case Results
## Bundle Configuration (4)

- **Time 2620 s**
- Formation of debris bed in center, water level rise more intensive in R6



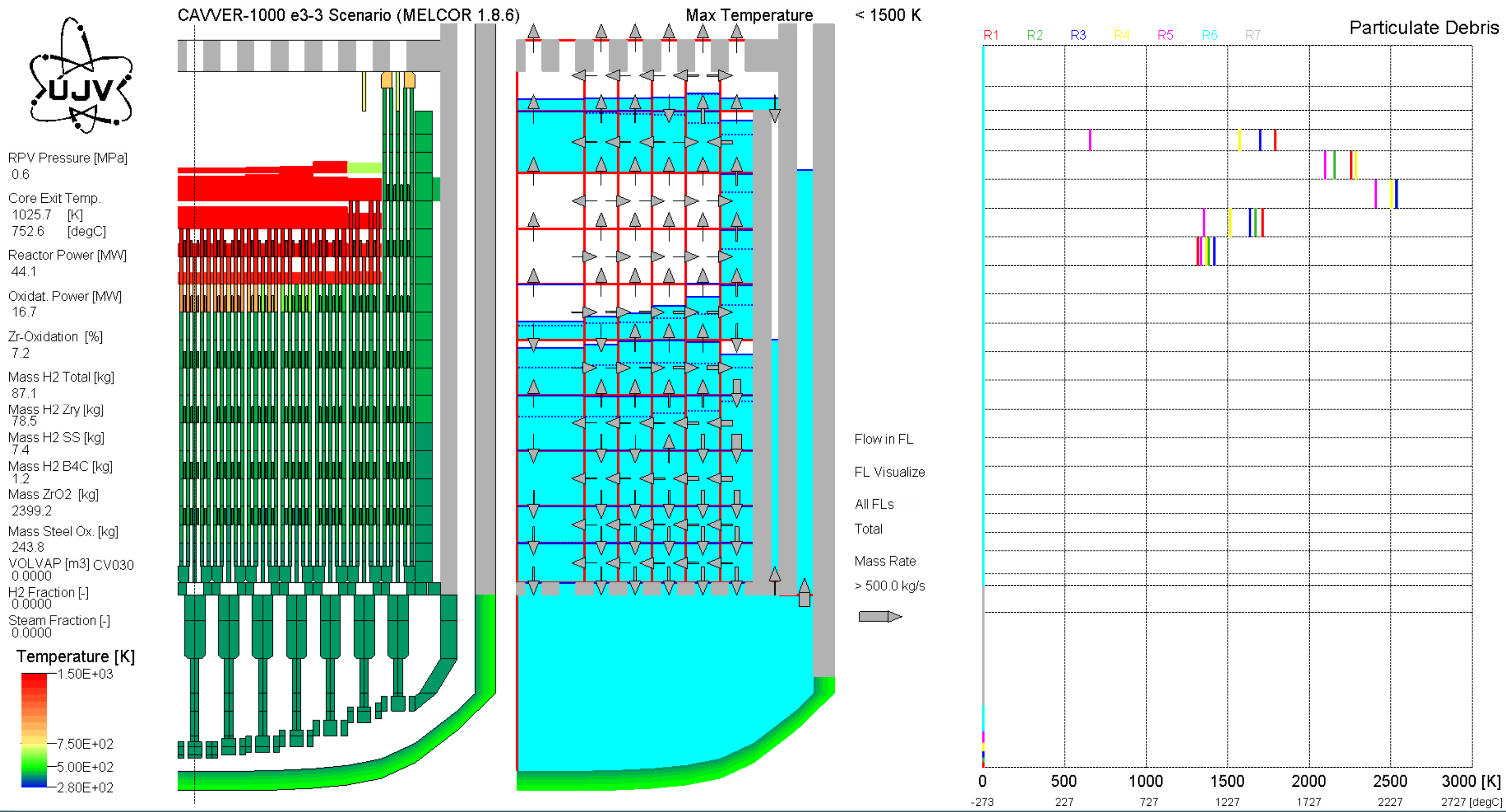
# M186dc2 Case Results
## Bundle Configuration (5)

- **Time 2670 s**
- Formation of debris bed in center, water covers debris bed, void formation



# M186dc2 Case Results
## Bundle Configuration (6)

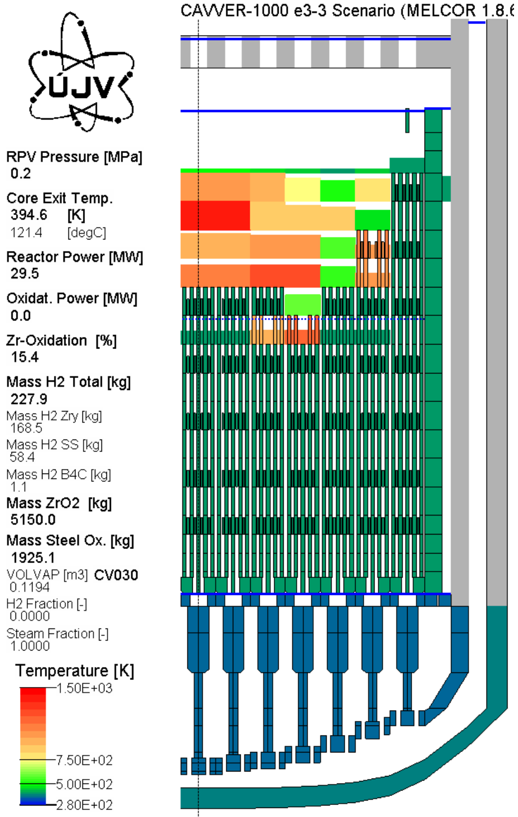
- **Time 2720 s**
- Debris bed in center remain hot with void cavity



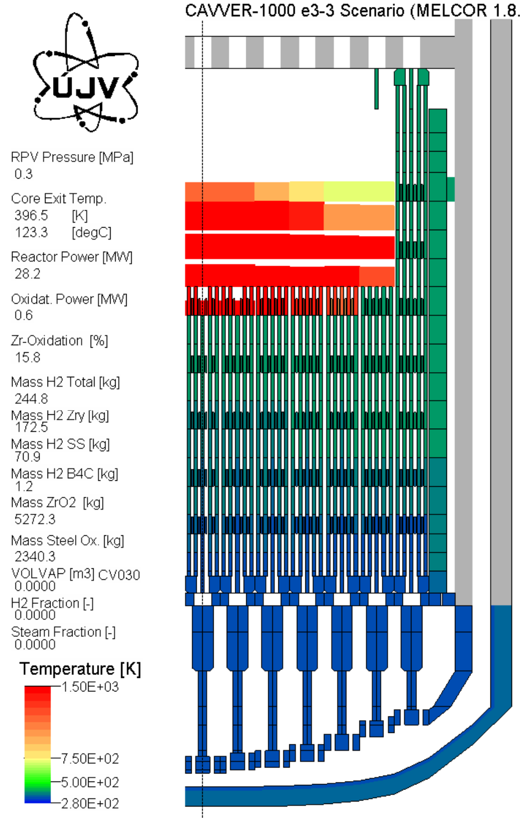
# Comparison of Results
# Final Bundle Configuration (2)

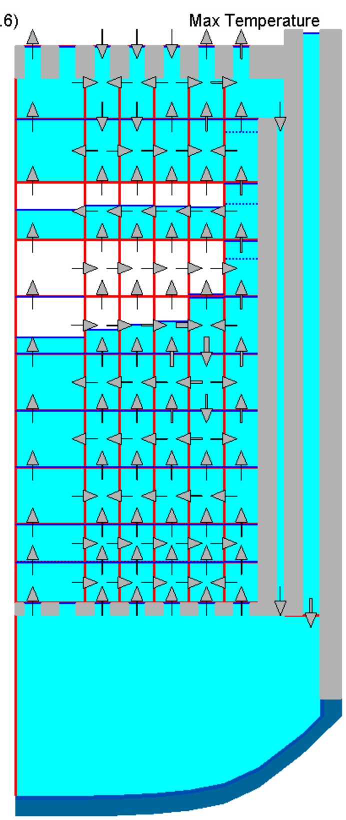
- Time 9000 s – end of calculation

M186r3

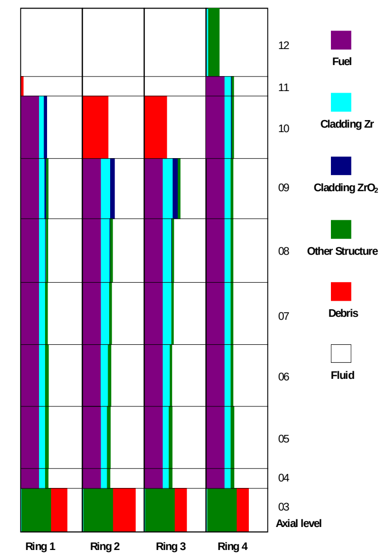



M186dc2




M183



# Summary, Conclusions

- Comparison of three simulations of reflooding scenario for VVER-1000 reactor performed
  - MELCOR 1.8.3 ([dsp1] 1999) with simple nodalization
  - MELCOR 1.8.6 with standard plant approach
  - MELCOR 1.8.6 with best practices to COR-CV-FL (very high CPU)
- Confirmation of too slow heat up rates during core uncovering in M183
  - Originally compared with SFD codes ICARE2 and SCDAP/RELAP5, M186 simulations in accordance
- Significantly higher hydrogen generation predicted in M186 in comparison with M183
  - Good agreement between both M186 simulation for total mass of H2, but very different maximum generation rates
  - Maximum peak rate below 0.8 kg/s in M6r3 and 0.5 kg/s in M6dc2 (ICARE2 0.9 kg/s) – M6r3 generated more than 125 kg during reflooding, I2 only 30 kg

# Summary, Conclusions (2)

- First two simulations showed possibility to terminate SA progression and cool down core with only one HPI system, but
  - The most detailed simulation predicts non-cooled hot molten pool or debris bed
  - Reflood mass flow rate is only a little above 1g/(s rod), which is understood as a minimum value for successful core reflooding if peak cladding temperature
    < 2200 K [heh] ⇨ but this case was with higher CL temp.
  - Contradictory answers have to be understood as negative answer on coolability for this definition of scenario
    - At least activation of system with higher mass rate or more trains of this low mass rate system necessary
    - Testing of more nodalizations is very important, because application of the only one input model could result in wrong conclusion due to selection of inadequate one

[heh] W. Hering, Ch. Homann: Degraded core reflood: Present understanding and impact on LWRs, Nuclear Engineering and Design 237 (2007) 2315-2321

# Summary, Conclusions (3)

- Application of best practices for CRO-CV-FL had penalty in significantly higher CPU
  - Application of this approach seems not be necessary for all scenarios
    - Important for scenarios with counter-current flow in hot leg

- Modelling of spacer grids as SS seems be more realistic than approach with their modelling as part of cladding
  - It enables to terminate relocation of large debris particles

# End of Presentation

**Thank You for Your Attention**